Construction and Building Materials 125 (2016) 279–289

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Hygrothermal properties of blocks based on eco-aggregates: Experimental and numerical study

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HIGHLIGHTS

- The valorisation of eco-aggregates, produced by ACT, in concrete is studied.
- The carbonated aggregates have thermal performances as lightweight aggregates.
- The eco-materials allow to reduce heat losses compared to expanded clay.
- The eco-materials allow to reduce and regulate the relative humidity in a room.
- These materials can be used as insulating-load-bearing materials in building blocks.

ARTICLE INFO

Article history:
Received 11 December 2015
Received in revised form 1 June 2016
Accepted 11 August 2016

Keywords:
Waste recycling
Carbonated aggregates
Thermal properties
Moisture buffer value
Hygrothermal behavior

ABSTRACT

This paper presents a study of eco-aggregates produced by a new Accelerated Carbonation Technology (ACT) in a sustainable approach. These eco-aggregates, obtained by mixing industrial by-products or wastes such as ashes with carbon dioxide (CO_2), have some characteristics which make them useful in the field of construction materials such as natural aggregates replacement in concrete or mortar. Hygric and thermal characterizations were performed on carbonated aggregates with adapted methods. The results have been compared to that obtained with two reference aggregates: natural gravel and expanded clay. Then thermal and hygric behaviors of concretes-based on carbonated aggregates were analyzed and discussed in the field of construction. These results proved that carbonated aggregates can be valorized through the manufacturing of concrete building blocks with several advantages: mechanical strength, thermal and hygric inertias. Experimental properties allowed a numerical/digital simulation in dynamic conditions for a simple and multilayered wall using the SPARK object-oriented simulation environment that is adapted to complex problems. Their performances were compared to those of concretes based on two reference aggregates in order to highlight the feasibility of manufacturing building blocks.

1. Introduction

The industry is increasing with the global population which generates a strong demand for natural resources used in the field of building construction. Moreover the construction industry is particularly concerned with the environmental impact of materials especially in terms of energy savings and raw materials. Therefore, the durability of materials is one of the major challenges of innovation and technology transfer. Alternative solutions to raw aggregates are currently under consideration to meet this challenge [1–7]: fibers from plant resources, recycled concrete. Indeed, the recycling of concrete allows to reduce the amount of waste to landfill. The use of recycled materials has become a major issue in sustainable development policies. The European Directive 2008/98/CE [8] aims at recycling inert waste at 70% by 2020. In the light of this, many studies have carried out on this issue [eg. 1,5,6,9]. However, among other waste streams currently landfilled, residues from thermal process (incinerators) represent the most significant volume. Therefore it's essential to focus on these materials to reduce the landfill of waste and the extraction of raw materials.

Moreover, reducing carbon dioxide emissions in the atmosphere is also a major challenge. Thus, a new technology, the Accelerated Carbonation Technology – ACT, was developed by the

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http://dx.doi.org/10.1016/j.conbuildmat.2016.08.043

Nomenclature

Symbol	*Definition unit*
Cu	uniformly coefficient (–)
Cc	curvature coefficient (–)
λ	thermal conductivity (W/m.K)
ε	fraction volume (%)
C_p	specific heat capacity (J/kg.K)
φ	heat flow density (W/m)
ΔT	temperature difference (K)
ρ	density (kg/m^3)
e	thickness (m)
MBV	moisture buffer value (g/m^2.%HR)
Δm	moisture uptake/release (kg)
RH	relative humidity level (%)
S	exposed surface (m^2)
E	thermal effusivity (J/m^2.K^1.s$^{1/2}$)
a	thermal diffusivity (m^2/s)
t	time (s)
τ	time period (s)
x	wall thickness (m)
φ_{ray}	radiation heat flow (W)
T	temperature (°C)
T_s	surface temperature (°C)
h_c	convective heat transfer coefficient (W/m^2.K)
θ	amplitude of temperature (°C)
T_{ic}	interface contact temperature (°C)
Pf	penetration depth (m)
A_k	available surface of material (k m^2)
V	volume of the room (m^3)
HIR*	hygric inertia of room (kg/(m^3.%HR))
R_v	gas constant (for water vapour $R_v = 462$ J.kg^{-1}.K^{-1}) (J/kg.K)
P_{ve}	partial vapour of outdoor air (Pa)
P_{vi}	partial vapour of indoor air (Pa)
$P_{v,sat}$	saturation vapour pressure (Pa)
G_{vp}	indoor vapour production (kg/s)
n	air change rate (l/h)

Indices	*Definition*
Eff	effective
U	upper
L	lower
A	air
P	particle
inf	lower
sup	higher
max	maximum
min	minimum
exp	experimental
agg	aggregate
S	solid particle
int	internal
ext	external
out	outdoor
s	surface

University of Greenwich and patented by Carbon8Systems [10]. The ACT carbonates waste (solid residue from thermal treatment) with carbon dioxide-enriched air (CO_2) to quickly form carbonated eco-aggregates. The carbonation process is able to treat many industrial material residues with high CO_2 concentrations. For example, paper ashes or sewage sludge are suitable for accelerated carbonation [11]. Fly and bottom ashes from household waste incineration [12,13] represent a significant stream of waste, which is currently mostly landfilled. The ACT offers their valuation and is therefore an interesting alternative to landfill regarding economic and ecological benefits.

Furthermore, minerals and polluting residues are chemically stabilized by the formation of insoluble carbonates and physically stabilized through the formation of compact aggregates [13–19]. The inerting mechanisms have been described by Fernández Bertos et al. [18]. Thus, during the carbonation, high quantities of CO_2 are absorbed to produce carbon negative aggregates which could substitute the natural raw materials used in building industry and public works. These eco-aggregates have low bulk densities (under 2000 kg/m^3) and are classified as lightweight aggregates, which gives them lots of advantages including thermal properties [20]. The thermal insulation, impacting the comfort and the energy use of buildings, is currently a major challenge [21], particularly in the context of long-term sustainable development and preservation of natural resources [22]. This study proposes a feasibility study on the use of eco-aggregates in the manufacturing process of building blocks. A first part is dedicated to the physical and thermal characterization of two eco-aggregates. Then, the hygrothermal properties of concretes-based on eco-aggregates, are conducted. Results are discussed by comparison with concretes based on expanded clay and natural gravel aggregates. Finally the mineral study of the thermal behavior of concretes based on eco-aggregates is carried out at the usual scale (single layer wall and multilayered wall). Finally, the hygric behavior of concrete made from recycled aggregates are compared to those of concrete based on reference aggregates (expanded clay and natural gravel).

2. Materials and methods

2.1. Characterization of aggregates and formulation of concretes

Two aggregates, produced by the ACT, are studied. They are based on Air Pollution Control residue (APCr) and on a mix of paper ash and quarry fines. The aggregates, respectively named C8 and PA have a bulk density of 1096 kg/m^3 and 879 kg/m^3; they therefore belong to the lightweight category. Their properties are compared to those of two reference aggregates, an expanded clay named EC with a bulk density of 698 kg/m^3 used as lightweight reference and a natural gravel named O with a bulk density of 1362 kg/m^3. C8 and PA aggregates have a porosity of 29% and 27% respectively and are more porous than EC aggregate which has a porosity of 17%. The O aggregate has the lower porosity with 3%. The high porosity of carbonated aggregates leads to a high water absorption rate, similar to EC aggregate (around 20%), while O aggregate shows a water absorption rate near 2%. We can deduce that these lightweight aggregates must previously be moistened when manufacturing concretes.

The particle size distribution of the aggregates according to NF EN 933-1 [23] is showed in Fig. 1. C8 aggregates are composed of more tiny particles with a size less than 2 mm (exactly 16.7%), than reference aggregates with 0.4% and 0.1% for aggregates O and EC respectively or than PA aggregate with 2.8%. Moreover the granular extent is established by uniformly (or Hazen) and curvature coefficients, respectively Cu and Cc, which are based on the sieve analysis (see Table 1). The exploitation of these parameters shows that C8 aggregate is a well-graded and moderately-stored gravel ($Cu < 4$ and $1 < Cc < 3$) while other aggregates are poorly-graded